Hybrid Propulsion Technology Development for a Potential Near-Term Mars Ascent Vehicle

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Abstract— **A technology development program for a potential hybrid Mars Ascent Vehicle (MAV) is currently underway to enable its infusion into a potential Mars Sample Return (MSR) campaign as early as 2026. A NASA team from the Jet Propulsion Laboratory (JPL), Marshall Space Flight Center (MSFC) and Ames Research Center (ARC) is leading and coordinating this program. A new propellant combination: the wax-based fuel, SP7, and MON-30 were proposed for a hybrid option for the MAV propulsion system several years ago. Since that time, hotfire testing with a similar propellant combination (SP7/MON-3) has been completed and a pathway to achieving high performance with the flight propellant combination is currently being pursued. Highlights of the progress to date and plans for risk reduction and the next steps in hybrid technology will be presented.**

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1. INTRODUCTION

The feasibility of a potential Mars Sample Return (MSR) campaign is being studied jointly by NASA and ESA [1], with the Mars Ascent portion of MSR is being considered for launch from Earth as early as 2026. [2] To meet this schedule, a hybrid propulsion system has been under investigation as a potential option for a MAV for several years. Launch from another planetary body has not yet been achieved and poses many challenges including what will likely be a novel propulsion system design, regardless of what type of propulsion technology is selected. Technology development has progressed from paper designs utilizing a completely new propellant combination, to demonstration tests at approximately full scale with a representative oxidizer. This year, the testing will culminate with full scale tests of the desired propellant combination in relevant environments.

Firm requirements for a MAV are still years away at best. Therefore, a design that closes under flexible assumptions is being pursued. At this time, constraints based on the Sample Retrieval Lander (SRL) interface are being used to size the MAV system (see Figure 1). Two SRL designs are currently being studied: a Propulsive Platform Lander (PPL) and Skycrane Delivered Lander (SDL). These options are described in more detail in Ref. [1]. At this point, it is assumed that either design will place the same geometric and mass constraints on the MAV.

Figure 1: Concept for a SRL with a hybrid MAV

The notional design must fit within a mass of 400 kg and a length of no greater than 3 m, with a strong desire to reduce that length even further. The payload is currently being taken as the difference between the allocated masses and the 400 kg Gross Lift Off Mass (GLOM). The temperatures to which the MAV may be exposed on Mars will drive the design. The assumption at this time is that the MAV will be exposed to a range of temperatures from -40 C to +40 C over its lifetime and will be launched at -20 C. This assumption is evolving with the time period (seasons) that the MAV is expected to be on the surface of Mars. A baseline design has been formulated by the NASA team. However, this paper will not focus on a specific design, but will instead highlight areas requiring technology development in order to demonstrate the drivers for this potential design by the end of summer 2019.

2. Potential Hybrid Design

Several potential hybrid designs have been published in the past. The most relevant of which was from the Point of Departure Review (PoDR) [3] in late 2016. The conceptual design has evolved over the past several years, most notably with the increased mass of up to 400 kg. Every time the potential payload increased, the propulsion system, and corresponding support masses would increase. Instead of continuing to react to changes in the payload and subsystem masses, the propulsion team is designing to the maximum, accommodatable size of 400 kg. The current estimate for the payload and required structure is about 12 kg. The MAV focus for the propulsion team has remained on the technology development of the novel propellant combination and the design has matured along with the tests. However, there is still a substantial amount of work to be completed.

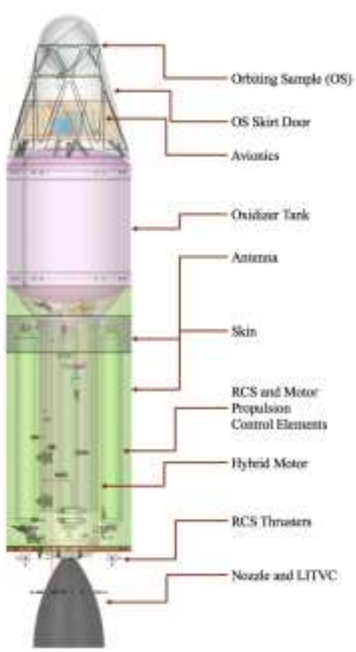

Figure 2: Notional design for a hybrid MAV (from PoDR)

3. Propellant Combination

Fuel

SP7 was developed specifically for this application. It is a wax-based fuel with a higher melt temperature and viscosity than neat paraffin. The increased viscosity precludes it from being spun cast. Currently, fuel grains are being produced in segments. The SP7 is cast as a liquid in oversized “cake pans” and cooled in a temperature controlled oven. This process takes approximately one week. After cooling, the fuel grains are machined to the desired inner and outer diameter and faced on both sides. Typically, one MAV-scaled fuel grain is made up of four segments.

Figure 3: Three of the four segments making up a full-scale fuel gain are shown being packaged for shipment.

Residual stresses

SP7 has interesting phase change properties and a high coefficient of thermal expansion. In transition from the liquid to solid phase, it shrinks between 15-20%. The material cools from the outside inward. A solid crust forms on the outer sections as they cool first and the inside cools slowly and retracts as the heat is removed. Therefore, the inside of the pulls on the outside of the grain, leaving residual stresses within the segment.

Early attempts at casting SP7 at MSFC allowed molten SP7 being to cool at ambient conditions. Thin sections (several inches) of material cast in this way would typically survive. However, about half of the thicker sections (more than about 10 inches) would crack during cool down. Attempts at utilizing a mandrel to form the center port in the grain also resulted in cracking. Attempts to put soft material around the mandrel, to account for the grain port, had poor success rates. Some mandrels would leak, others would be another cooling path, creating a void annulus in the grain. Eventually, the mandrel concepts were abandoned, since there would need to be post cure machining anyway.

Through trial and error and multiple suggested attempts/techniques to fix the residual stress problem and related grain failures, it was decided to slowly cool the grain to get a more uniform temperature at the phase change. An oven was purchased to control the temperature throughout the cool down process. This resulted in grain segments that did not crack during the cooling process. Taller pans were made in house to create the four segment fuel grains that are now the baseline and a controlled cooling process is used exclusively.

Controlled cooling has not been without issues. Minor changes to the pan configuration and therefore cooling process did result in grains that cracked. These changes included covering the top of the pan with a plywood sheet (with holes for air flow) to keep it round. This implies that even the grains that survive the casting process maintain a relatively high stress state. [4]

There are modeling efforts planned to better understand and reduce the residual stresses in the grain. However not all the material properties for SP7 are known at this time. Southern Research is carrying out material testing on SP7 and results are expected in the Spring. Commercially available software will be used to study the phase change problem, once the material data is available.

A preliminary study has shown that annealing the grains (post-manufacture) dramatically decreases the residual stresses. This process caused a significant change the SP7 material properties in samples taken from ambient cooled grains. However, the results of annealing oven cooled grains have still not been completed. The oven cooling process reduces the residual stress, but there is potential that further reduction could still be achieved by subjecting the grains to another heating cycle after processing. Additional testing with the oven cooled samples is currently in process.

MON Oxidizer

Mixed Oxides of Nitrogen (MON) is a common space storable oxidizer. Most existing propulsion systems use MON-0.5 to MON-25, where the number stands for the percentage of NO in the mixture (by mass). The freezing temperature of N_2O_4/NO mixtures is given in Air Force Handbook [5]. The curve is very steep, with a difference of about 25 C between MON-25 and MON-30. MON-30 has been the desired oxidizer for the hybrid option in the recent studies, with a freezing point of about -80 C. This would enable storage down to about -70 C. However, current mission design indicates that the MAV and oxidizer can be kept above -40 C based on an updated mission timeline which does not have the MAV on the surface of Mars during the winter. A move to MON-25 was made in 2018 based on the new mission timeline and the availability of the oxidizer.

Information on N_2O_4/NO mixtures through MON-30 is available in Ref. [5], however, it is more readily available up to MON-25. This is an additional benefit to switching to MON-25.

One of the challenges (and benefits) of MON is that it is reactive with many materials. All potential components are being evaluated for compatibility, primarily using data from Ref. [5]. On the other hand, MON's reactivity makes it possible to consider it for hypergolic ignition. This will be discussed in Section 5.

4. Full Scale Testing

Two vendors have completed hybrid motor testing at near full scale over the past year and a half. Space Propulsion Group, based in Butte, Montana and Whittinghill Aerospace, based in Camarillo, California (with a test site at the Mojave Air and Space Port). Each brought many years of hybrid experience to this problem. Both teams developed their own design based on a provided specification and built the necessary test stand and feed system to work with MON-3. MON-3 was used as an analog for the higher NO concentration MONs because it is less expensive, easier to acquire and is has similar vapor pressures at atmospheric conditions to MON-25 at -20 C. Discussion of the suitability of this substitution has been discussed in Ref. [6]. Testing of the desired propellant combination will be completed in the near future. This will be discussed in Section 7.

Figure 4: Still from a hotfire test at Space Propulsion Group

Figure 5: Still from a hotfire test at Whittinghill Aerospace.

Testing successes during this period included almost full mission duration testing with a motor shutdown and restart without human intervention. Due to increased regression rate from the burn rate measured in smaller motors [7], future testing may need a slightly larger diameter motor to meet the required impulse for Mars orbit insertion or slight modifications to the regression rate of the fuel. There were some stability issues that have been overcome by changes to the motor internal design and the feed system throughout the first year of testing.

There are still some remaining risks to the propulsion system. The performance metric of choice for this motor is the C* efficiency. After a year of testing, it is still shy of the desired 95%, resulting in a lower specific impulse than desired. One of the vendors experienced high erosion at the nozzle throat, which leads to low C* efficiency. This lowers the chamber pressure and nozzle area ratio during the test, which leads to decreases specific impulse. Conversely, early tests with substantial instability were not used to determine C* efficiency, as instabilities can often artificially inflate the C* values that would be seen in a stable motor.

At the end of the test campaign, the vendors also delivered motor designs for a Mars application. Both were heavier than required for flight. Therefore, with the benefit of knowledge from both vendors, a new design has been put forth by the NASA team to minimize system mass, while focusing on simplicity whenever possible. The two companies have been asked by NASA to join forces and work improving this single motor design going forward.

5. HYPERGOLIC IGNITION

Previous studies suggested that hypergolic ignition would be the best option for the MAV [3]. Two methods of hypergolic ignition are currently being considered. The first employs the liquid Triethyl Aluminum and Triethyl Borane (TEA/TEB) with the MON oxidizer. TEA/TEB is most commonly used with oxygen as an ignition mechanism. However, Purdue completed a drop test with N_2O_4 that indicated it is hypergolic with Triethyl Aluminum and therefore could be used in a MAV ignition system. The second employs hypergolic materials in solid additives. Purdue [8] and Penn State [9] researched this field in 2017 and Purdue has continued on with testing in 2018.

TEA/TEB Ignition

TEA/TEB has been used in hybrid rockets in the past for both ignition and enhancement of stability. American Rocket Company originally patented the concept based on their testing with liquid oxygen. [10] The combustion of TEA/TEB and oxidizer helps vaporize the remaining oxidizer and the additional heat improves flame holding in the motor. TEA/TEB as a stability enhancement is a proven technique used in hybrid motors.

Figure 6: Hybrid motor ignition with TEA/TEB

There are disadvantages to using a TEA/TEB system for a potential hybrid MAV. Since the TEA/TEB is hypergolic with MON as well as oxygen, handling of the system becomes more hazardous. The TEA/TEB system needs to be isolated during ground processing, launch from Earth, cruise, Entry Descent and Landing (EDL) and during the ground environment. Then TEA/TEB system has to be turned on during the two currently required burns of the motor. (These are all similar requirements to the MON feed system.) However, carrying two fluids which are hypergolic with each other increases the safety concerns of the system. Also, the TEA/TEB system accounts for nearly 20% of the total component count in the feed system. Finally, while TEA/TEB doesn't freeze within the temperatures being considered here, the available energy for ignition and head addition during combustion needs to be evaluated at low temperature.

Solid Hypergolic Ignition

Testing at Purdue and Penn State identified several solid hypergolic options using different amide formulations. Unique processing steps were developed by Purdue to incorporate the material into SP7. [11] These materials have used to hypergolically ignite about two inch diameter MON-3 motors multiple times. Techniques that could be employed in a full-sized MAV hybrid are being investigated at sub scale.

Figure 7: Hypergolic ignition of N_2O_4 and SP7/Sodium Amide in a 2-inch motor at Purdue University.

The advantages of a solid hypergolic material embedded in the SP7 is that it is already contained in the motor case. No additional containers, plumbing or valves are required. It also dramatically simplifies the ignition process: the main oxidizer valve is opened and the motor ignites after the MON contacts the additive.

However, there are also several disadvantages of the solid additives. The materials are sensitive to moisture, complicating the ground handling procedures and requiring the fuel grain to be isolated from contact with air. This could limit the use or positioning of solid additives in fuels with composite cases where the case is wrapped around the fuel. In this case, water could not be used to proof test the motor with the grain already installed. Wax is hydrophobic and it was thought that the SP7 fuel could be used to protect the additive from exposure to moist air. However, completely coating the additive in fuel also protects it from exposure to MON and prevents the hypergolic reaction.

6. Liquid Injection Thrust Vector Control

The hybrid design requires guidance to deliver the samples into a sufficiently accurate Mars orbit. Liquid Injection Thrust Vector Control (LITVC) has been thought to be the lowest mass option; however, other options are being considered. Very little deflection is required, between 1-2°. The design is currently envisioned with eight, fast acting, lightweight valves working in pairs every 90° around the nozzle. One valve would provide sufficient flow for a ±1° deflection and both valves would provide ±2°.

Candidate valves were employed in ground testing this year. However, the Commercial Off The Shelf (COTS) valve seat material was only recommended for limited exposure to MON. Some leakage was observed. Therefore, modifications would be required for flight. Recently, JPL has worked with Moog to modify ones of these lightweight valves for gaseous oxygen service. [12] Similar changes are envisioned for MON compatibility.

Technology Development

The vendor motor tests demonstrated LITVC performance through three tests. Figure 8 shows the plume during normal operation (top) and LITVC actuation (bottom). A shadow near the nozzle exit can be seen between the two images representing this actuation. MON-3 liquid is injected through a single valve in these tests with the aim of creating about a 1° deflection.

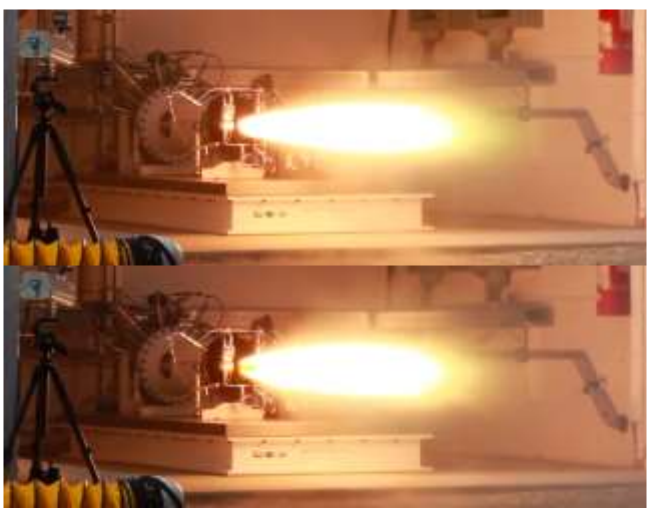

Figure 8: Top: Still image of FT-02 test at Whittinghill Aerospace during normal operation. Bottom: Still image during LITVC operation.

This test (and all full-scale tests to date) have been completed at Earth ambient pressure and temperatures. In order to keep the nozzle flow from separating, a shorter nozzle must be employed and the LITVC propellant must be injected at a different axial position (x/L) on the nozzle. The modeling effort of the LITVC system was all done with Mars type nozzle expansion [13] and is currently being updated based on the test data collected. A Mars/vacuum expansion nozzle test to determine LITVC performance is planned for late summer of 2019. The feasibility of measuring the plume deflection via infrared camera and force measurements is currently being investigated. This data will be used to validate the modeling effort and update the LITVC propellant usage for the potential MAV design.

7. FY19 Plan and Future Work

The goal of this technology development program is to have demonstrated the major milestones required for a hybrid MAV design that closes under the current assumptions for Mars Sample Return by the end of summer 2019. A substantial amount of research will be required to ensure this possibility. The highlight of this effort will be testing of a thermal cycled, full-scale hybrid motor under relevant conditions. To realize that goal, the propellant combination must be fully characterized, hot-fire testing must be completed to confirm the behavior and all potential materials need to be analyzed. Trades will be carried out on many design features including the TVC system and motor case material.

Up to six full scale tests will be completed in Fiscal Year 2019. Three tests focus on motor development for the wax-based fuel and MON-25 oxidizer. A primary goal of the first test is to test the desired propellant combination at low temperature with a flight-like ignition sequence. The next two tests will continue to evolve towards more flight like conditions and will focus on mitigating the issues discovered in the previous year of testing such as low C* performance (<95%) and high nozzle erosion. These tests will be carried out at Whittinghill Aerospace's test facility in Mojave, CA.

Multiple subscale tests will be completed at Space Propulsion Group's test facility in Butte, MT. The driving force behind these tests is to determine the regression rate of a slightly modified version of SP7 with the target of realizing a 15% reduction. Theoretical calculations have been completed and a new formulation has already been created. The target formulation will be tested with MON-3, since that oxidizer is already on hand and the new data will be easy to correlate with the previous data (which is also with MON-3). In addition to the predicted 15% reduction formulation, small modifications both above and below the target formulation will also be tested as a contingency for if the target formulation does not behave as predicted. Once the regression rate testing is finished, several full-scale tests will be completed. These tests will mainly be focused on testing with a light weight motor case to confirm the design desired for flight can be fabricated.

Solid hypergolic additives are still being evaluated by Purdue. They will test hypergolic ignition with MON-25 under low pressure conditions this year. However, the full-scale testing will continue to use a TEA/TEB ignition system this year. The potential for adding solid additive to a potential system will be evaluated and a decision should be made by the end of the fiscal year.

If a hybrid option is to be considered for flight, its qualification must be discussed. A standard for a hybrid rocket propulsion system qualification process does not exist. A qualification plan of a hybrid motor for a potential MAV is being developed and is presented in Ref. [14]. Experience from solid and liquid propulsion systems is drawn upon for this plan. Additionally, specifics for the Mars environment are taken into consideration in this plan.

While the technology development program is underway, MSFC will be leading a study to design complete concepts for both a hybrid and solid version of a MAV vehicle. This study will be completed by May and take early test results into account whenever possible. This study will incorporate personnel from all relevant disciplines, including: thermal, avionics, power, etc. and will update the PoDR design that has been used as a baseline. Additionally, this study will work closely with the MSR and SRL studies being led by JPL to make sure the MAV concepts fit within study constraints for the higher level architecture.

8. SUMMARY

A technology development program is underway to determine feasibility of the hybrid option for a potential Mars Ascent Vehicle as part of a potential robotic Mars Sample Return Campaign. Substantial strides have been taken in the propulsion system development. Full scale hotfire testing has been completed at two vendors and the development is ongoing with both vendors joining their efforts. Hypergolic ignition has been researched and demonstrated using multiple options. The potential design is continually updated based on the developments of the development program. The goal is to demonstrate a design that closes by the end of summer 2019.

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